EXPERIENCE GAINED IN OPERATION OF THE VLF ATD LIGHTNING LOCATION SYSTEM

Anthony C. L. Lee
Meteorological Office, Bracknell,
Berkshire, RG12 2SZ, United Kingdom

ABSTRACT

The UK Meteorological Office's VLF Arrival Time Difference (ATD) system for long-range location of lightning flashes started automatic international issue of lightning-location products on 17 June 1988. Data from before and after this formal start-date have been carefully scrutinised to judge performance. Techniques for estimating location accuracy include internal consistency and comparisons against other systems. Other areas studied were range (up to several thousand km); detection efficiency, saturation effects in active situations, and communications difficulties (for this redundant system); and spurious fix rate.

Care has been taken to assess the potential of the system, in addition to identifying the operational difficulties of the present implementation.

INTRODUCTION

The Meteorological Office's Arrival Time Difference (ATD) system for long-range lightning-flash location operates in the very low frequency (VLF) band, where lightning atmospherics ('sferics') at frequencies near 10 kHz propagate within the earth-ionosphere waveguide to great distances [1, 2]. The system has a nominal service area of 40W–40E 30–70N, which exceeds the combined areas of the USA and Canada, although strokes can be usefully located well outside this area at ranges of several thousand kilometres. The bulk of the nominal service area is shown in Fig. 1, and this is serviced by just seven ATD outstations whose eventual deployment is shown.

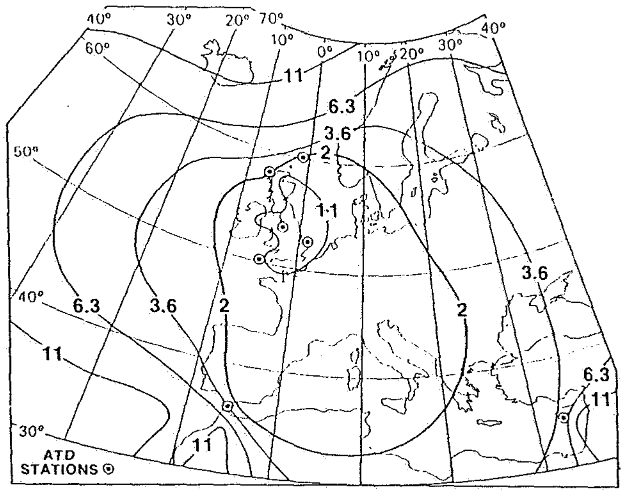

Figure 1: Seven outstations (five UK; Gibraltar, Cyprus) cover the 40W–40E 30–70N service area. Contours of RMS km fix error, for 5 μs *ATD* errors, are superimposed. Smaller *ATD* errors are realistic, with proportionally reduced fix errors.

OPERATION OF THE ATD SYSTEM

In the ATD system, a single lightning stroke produces sferic waveforms which are received through their vertical electric field, and are band-limited (eventually to 3 dB limits at 8.1, 11.7 kHz) at the unmanned outstations. From each outstation the digitised sferic waveform, together with the instant of time (or epoch) of the first digitisation sample for the waveform, is communicated to the control station. The detailed technique involves each outstation storing all the data that it observes above an analogue threshold, and forwarding selected data on request to the control station.

At the control station one waveform is chosen as a reference, and the other waveforms are each correlated against this to extract the arrival time difference of the sferics against the reference. Although digitisation samples are spaced at intervals of several microseconds, the sferic waveform is limited to a frequency range well below the Nyquist constraint, so that the underlying continuous waveform is arbitrarily well represented, and each measured arrival time difference value (ATD_M) can be estimated with adequate resolution — in this case well below a microsecond.

The most likely lightning stroke location (or 'fix') is estimated by its iterative adjustment to minimise the weighted differences between a set of theoretical arrival time difference values (ATD_{TH}) based on the assumed stroke fix, the known outstation receivers' coordinates, a modelled sferic phase velocity, and a spheroidal earth; and the set of measured arrival time difference values (ATD_M).

ESTIMATION OF FIXES, AND FIX ERRORS

The fixing process can be described more formally as the minimisation of $RESIDUAL^2(\theta, \lambda)$ with respect to the stroke coordinates ϕ, λ, where:

$$RESIDUAL^2(\phi, \lambda) = \frac{1}{(m-2)} \times \sum_{r=1}^{m} \left\{ \frac{ATD_{TH}(r, \phi, \lambda) - ATD_M(r)}{\sigma(r)} \right\}^2 \quad (1)$$

and:

m = No. of non-reference outstations (No. of ATD values).
r = Index of non-reference outstations.
ATD_{TH} = Theoretical ATD value.
ATD_M = Measured ATD value.
ϕ = estimated stroke latitude.
λ = estimated stroke longitude.
$\sigma(r)$ = ATD standard deviation for non-reference outstation.

The normalising factor $(m-2)$ accounts for the number of degrees of freedom (DOF) involved in fixing, so that with correct $\sigma(r)$ values the expectation for the minimum value of $RESIDUAL$ is unity. This can be used to form the basis of a technique for estimating the root mean square (RMS) values of $\sigma(r)$ provided some relation is assumed between them (eg. they are equal), and provided that measurements are averaged over many strokes.

Once the ATD standard deviations $\sigma(r)$ are known, they can be used to predict charts of absolute fix accuracy. Fig. 1 shows fix error (RMS km) of the eventual ATD outstation deployment over most of the service area under the assumption that $\sigma(r) = 5\ \mu s$, and that all seven outstations are involved in every fix.

In practice there may be bias in the differences between theoretical and measured ATD values, due to errors in the algorithms converting local timescale values to International Atomic Time ('timescale errors'), and modelling sferic velocities ('propagation errors'). Lee [3] extends the above argument by considering many strokes occurring within a short time-period (timing errors are constant) and within a fairly small geographical region (propagation errors are constant), so that any systematic bias offsets will be constant, and may be estimated as degrees of freedom along with the stroke locations.

If this is done, the remaining ATD standard deviation $\sigma(r)$ will be reduced from values representative of absolute fix error to a measure of the the irreducible ATD scatter remaining after bias removal. In this case the charts of fix 'error' for bias-reduced $\sigma(r)$ will correspond to charts of scatter in the fixing process. This information is important as it represents the limiting ATD system performance if bias errors can be adequately alleviated.

ABSOLUTE AND RELATIVE FIX ERRORS FROM INTERNAL EVIDENCE

TRIALS RESULTS

Initial indications come from 1978–9 trial results, with just four experimental outstations — three in the UK and one in Gibraltar [1].

In winter conditions lightning tends to occur in isolated clusters, mainly over the ocean:

- On one occasion, of 41 Mediterranean flashes no fewer than 17 occurred in groups of 1.7–10.7 km diameter — in spite of the 1000–2600 km range to most outstations.

This is likely to be an over-estimate of fixing scatter, as the observed scatter must include the physical separation of the observed strokes.

Absolute ATD system errors were estimated from $\sigma(r)$ from the trial data:

- Over the entire trial, $\sigma(r)$ values for absolute errors (no biases removed) were found to fall within the range 3.3–10.9 μs — with the larger values associated with minor equipment failures.
- The more representative lower value is smaller than the 5 μs used in Fig. 1.

With full operational outstation deployment, Fig. 1 suggests $\sigma(r) = 5\ \mu s$ gives 1.5–2 km fix errors in the Mediterranean. However, the more restricted trial outstation deployment degrades predicted absolute fix errors to 7–12 km. As expected, this is somewhat larger than the apparent fixing scatter, but not to such an extent that these results are inconsistent.

Table I. Pre-Operational Results for daytime strokes over southern UK [3].

Date:	Jul 29, 1987	Sep 05, 1987
GMT:	1500–1511	1430–1900
Strokes:	41	275
Absolute $\sigma(r)$:	6.5 μs	—
Abs. Fix Error:	3 km	—
Relative $\sigma(r)$:	1.6 μs	1.3 μs
DOF:	47	365
Scatter :	700 m	630 m

A trial case [4] involved a tight group of intense sferics apparently associated with an organised storm near 45N 3E on the Massif Centrale in France. *ATD* variance over several strokes indicated an absolute fix error of around 5 km in this region. The RMS spatial scatter of this group was 1.1 km, but it appeared to travel consistently with local winds:

- If a uniform velocity fitted to this data is subtracted, the best estimate RMS Lagrangian spatial scatter (taking correct account of lost DOF) is reduced to 0.5–0.6 km.

However, as this group contained only 3–5 flashes, all that can be said with reasonable (90%) confidence is that the fix scatter was representative of a population scatter that fell within 2.5 km RMS.

No attempt was made to eliminate bias from small regions of trial data, because data rates were too low to produce results at high confidence level.

PRE-OPERATIONAL SYSTEM RESULTS

During its pre-operational phase, the five UK outstations of the non-experimental ATD system were installed, and the system tested with frequent rebooting of sub-systems and other experimental activities. Routine sanitisation activities such as spectral calibration were not carried out, and minimum attention was paid to epoch calibration. In spite of this, the data were amenable [3] to determination of bias-removed $\sigma(r)$ because such systematic offsets are eliminated; results are presented in Table I.

NAVSTAR Epoch calibration was carried out at all outstations shortly before the Jul 29 case, so local outstation timescales were well established:

- During 1500–1511 GMT 41 strokes were received in the southern UK. Their analysis (during which offsets were set to zero, implying no bias corrections) yielded $\sigma(r) = 6.5$ μs.

If all five outstations contributed to each fix in the southern UK region with $\sigma(r) = 6.5$ μs, then fix errors would have been 3 km. A comparison was made [3] with 5 km radar rainfall data, and close agreement was found between sferic fixes and isolated squares of intense rainfall, although it is known that peak rainfall and lightning are not precisely coincident.

Allowing fitted offsets to eliminate bias effects reduced $\sigma(r)$ to its (relative or scatter) error of 1.6 μs, giving a fix scatter of 700 m. Such small scatter levels are physically realistic [5]. Clearly, there was substantial bias in the absolute fix error — perhaps due to propagation effects.

A similar exercise was carried out on a much greater data set from Sep 05 (Table I). This data occurred 38 days later, after power re-starts and operator re-establishment of epoch using Loran-C data only. The offsets were different between the two dates, and gave clear evidence that relative to the Beaufort Park epoch, other outstations had been shifted by 10, 20 or 30 μs (± 1 μs) because of the 10 μs cycle ambiguity of Loran-C.

- Any system which relies only on Loran-C timing can suffer ambiguities of multiples of 10 μs if no steps are taken to remove the problem. In the ATD system the problem can be identified and removed using the techniques presented here, or by using Omega reception facilities.

For this reason the absolute $\sigma(r)$ values were larger, and are not considered here.

Bias elimination reduced $\sigma(r)$ to a similar 1.3 μs, and a scatter of 630 m for five-station fixing.

EARLY OPERATIONAL DATA

The Gibraltar and Cyprus outstations were subsequently deployed to the operational configuration, although communications initially proved troublesome, limiting data availability.

With long-baseline deployment, interest lies in whether the effects of long-range propagation degrade $\sigma(r)$. The most stable VLF propagation occurs around local mid-day over the path, and data were found for 1000–1200 GMT on Dec 04, 1987 covering three distinct groups of strokes (first four columns of Table II) located west of Portugal (group A), 1200 km east of Atlantic City (group B), and 1000 km west of Sierra Leone (group C).

Analysis results allowing offsets to eliminate bias are presented. The three $\sigma(r)$ values were ~30% larger than the UK-stroke values at 1.91, 1.75, 1.80 μs respectively. The associated (relative) fix scatter based on seven outstations (6 for C, as no sferics were received at Cyprus) are 1.3, 7.3, and 7.3 km — small values in spite of the great ranges involved.

Table II. Analysis of three mid-day groups of strokes for Dec 4, 1987. These are analysed to find Relative $\sigma(r)$ separately; and also as a single composite group with fitted phase velocities [3].

Group:	A	B	C	A+B+C
Location:	W of Portugal	1200 km E Atlantic City	1000 km W Sierra Leone	—
Lat, Long:	38.3N, 11.6W	40.3N, 61.1W	8.2N, 21.1W	—
Strokes:	34	48	48	130
Rel. $\sigma(r)$:	1.91μs	1.75μs	1.80μs	3.30μs
DOF:	88	140	170	394
Scatter:	1.3 km	7.3 km	7.3 km (6-station)	—

The three groups were composited, using a single set of offsets, to see how the wide geographical area would further degrade $\sigma(r)$. The sferic paths lay over regions of quite different surface conductivity, including sea, normal land, and the Sahara desert — so phase velocities would be different. To make a crude allowance for this, different phase velocities were used for groups A, B; and two phase velocities were used for group C, depending on whether the path lay over land/sea or desert. The phase velocities were fitted as part of the overall minimisation process — and a further four degrees of freedom were subtracted to give consistent statistics.

The fitted sferic phase velocities were reasonably consistent with theoretical values. Scatter results are shown in the last column of Table II. A rather larger $\sigma(r)$ of 3.30 μs is produced, highlighting the crudity of the model phase velocity used. Nevertheless, this degree of timing scatter is considerably smaller than experienced as absolute timing errors — demonstrating that bias reduction can be effective even with geographically coarse propagation information.

During the previous evening (Dec 03) 49 strokes were observed to the far south-west of the service area, during a twilight and night-time path: results are presented [3] in Table III. Biases were eliminated by fitting offsets, but when all strokes were composited the extended range and variation in twilight conditions produced a large scatter of 11.9 μs. Breaking the data into more limited geographical and temporal ranges (but still retaining useful numbers of degrees of freedom) gave $\sigma(r)$ values of 1.3–2.0 μs, except for one result of 6.1 μs where it is likely that rapid twilight changes were taking place.

CONCLUSIONS FROM INTERNAL EVIDENCE

From the above discussion conclusions are:

- If no allowance for bias is made then $\sigma(r)$ estimates for absolute stroke locations are obtained. Values vary with details such as operator errors in setting timescales etc., but under correct operating conditions values of 3–7 μs are found.

Table III. Analysis of long-range night-time Caribbean and tropical Atlantic clusters for Dec 03, 1987 [3]. Offsets were fitted to eliminate bias.

Group	GMT	Lat/Long	DOF	$\sigma(r)$ (μs)
All	1900–2230	—	157	11.9
D	1925–2044	10.8N, 44.7W	21	1.3
E	2129–2214	11.1N, 39.4W	5	2.0
F	1906–2045	11.0N, 76.5W	18	6.1
G	2051–2214	11.5N, 74.4W	32	1.8
H	1909–2227	14.4N, 79.0W	46	2.0

- If suitable offsets can be found or predicted, then $\sigma(r)$ values associated with relative locations (or scatter) of around 1.4–2.0 μs can be obtained, even under twilight conditions.
- Twilight conditions will be the most difficult to predict because conditions change rapidly.
- Absolute fix errors, or scatter in fixing, are calculated by scaling charts like Fig. 1.

CURRENT ATD SYSTEM PROBLEMS

CYCLE MIS-MATCHING IN *ATD* EXTRACTION

Sferics travelling in the earth-ionosphere waveguide have a phase velocity which varies with frequency and path, associated with a group-velocity less than the phase velocity. Thus sferic waveforms change with propagation, and have a slightly different shape when received at each outstation.

This distortion may modify waveforms differentially to the point where the correlation peak used for *ATD*-extraction is highest for a mis-matched cycle — and an *ATD* value an approximate multiple of 100 μs (one carrier period) in error is obtained. This situation is usually associated with two similar-height peaks in the correlation, so that a warning of possible mis-match is obtained. In the present system the $\sigma(r)$ for that particular stroke and non-reference outstation is set to 100 μs. This is usually large enough to down-weight this *ATD* to the point where it plays little part in subsequent fixing.

Early experience demonstrated that this 'fail-safe' approach produced unacceptable data-loss. The problem could be bypassed by correcting waveforms to some intermediate range using an initial fix and a spectral propagation model. This has not been done, but a partial solution has been implemented by fitting a group velocity to experimental data, and using this to correct the envelope position of sferic waveforms to match the phase velocity.

Nevertheless, where the outstation complement is reduced and cycle mis-matching occurs, the result can be data-loss; or if the error is not detected, a poor fix.

Current alleviation of cycle mis-match wastes data. The quantity $\sigma(r)$ represents a conceptual Gaussian distribution of error. Recognition of a cycle-slip does not imply a Gaussian error distribution of width 100 μs; rather the Gaussian error distribution remains at the normal level, but there is a high probability of a catastrophic jump. Alternative *ATD* values are easily found from alternative correlation peaks, and the 'correct' value may be identified by examination of *RESIDUAL*. By this means the outstation data associated with the cycle-slippage is not lost, can take part in the fixing to provide redundant data (and hence maintain accuracy), and maintains redundancy for assessment of 'wrong cycles'.

The discrimination of this process depends on the ability to detect 100 μs *ATD* errors, flagged by unlikely values of *RESIDUAL*; and its sensitivity depends on the value of $\sigma(r)$. In practice, under current arrangements $\sigma(r)$ is not monitored by any on-line or off-line process, but is assigned by an operator. The value used is generally around 13 μs (rather than 3–7 μs), largely because of the perceived probability of an operator setting local timescales to an incorrect Loran-C zero-crossing! Unfortunately this is something of a self-fulfilling prophecy, because with such a large $\sigma(r)$ value any such incorrect operator settings are not highlighted by consistently significant values of *RESIDUAL*. Reduction of $\sigma(r)$ by bias-reduction techniques would sharpen discrimination.

COMMUNICATIONS PROBLEMS

Communications between outstations and control station is currently through dedicated low-speed (110 bits s^{-1}) telegraph lines. All are subject to surprisingly frequent outages, and if immediate reporting action is not taken (implying manpower-intensive monitoring) outages may become prolonged. This reduces outstation availability. The lines suffer higher bit-error rates than that for which the error-correction protocols were designed, causing some communications congestion.

For the UK outstations greater availability may be obtained by the redundancy and lower error-rate inherent in a properly maintained digital packet switched network, such as the Meteorological Office Weather Information System; and such systems may carry their own transparent fault detection and reporting systems. The variable packet-switched delays need not be a problem in this system.

The worst communications problems exist on the two overseas stations. This is unfortunate as the cramped deployment of UK outstations makes the overseas stations crucial to long-range fixing. Cyprus suffers particular problems as it is a low-priority shared line, which on frequent occasions becomes unavailable. Loss of Cyprus data degrades long-range performance to such an extent that there may well be a false economy in shared use. An earlier shared link to Gibraltar has now been replaced by an exclusive line.

If outstation spatial deployment were more uniform, alternative (possibly additional) communications through techniques such as meteorscatter could extend the packet network; the extra redundancy would improve channel availability and automatic monitoring.

The burden of monitoring communications lines and reporting outages is currently borne by the control station operators, mandating their presence. Line-fault detection must become more automated, with automatic reporting of outage to the permanently manned Meteorological Office communications desk for remedial action.

ISOLATED OUTSTATIONS

Current outstation deployment has most outstations cramped within the UK, with two isolated overseas stations, making fix accuracy crucially dependent on overseas outstations. Fig. 2 shows location error for 5 μs *ATD* errors using just five UK outstations in their current deployment (with the 'Aughton' outstation at the unfavourable Beaufort Park location). The 2 km fix error that existed over much of the Mediterranean is degraded to around 40–80 km, although degradation is less dramatic near the UK.

Long base-lines reduce fix error, but strokes observed by UK outstations may appear weak at the overseas outstations. Because of their low latitudes the Cyprus and Gibraltar outstations suffer reception of frequent sferics from intense tropical storms,

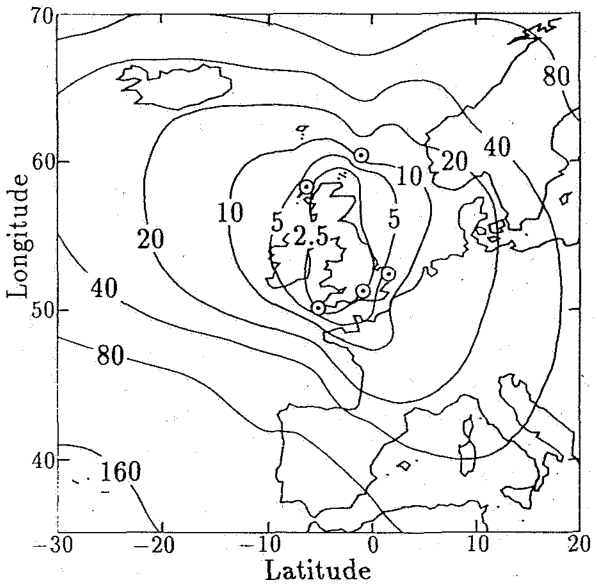

Figure 2: As Fig. 1, for five UK outstations in their current deployment. The 'Aughton' outstation is currently located at Beaufort Park.

which may prevent reception of the 'wanted' weak sferics. In particular, strokes to the north of the UK may not be received at either overseas outstation; and strokes in the western Atlantic will often not be received at Cyprus. This problem, added to communications outage, reduces overseas outstations availability — with a disproportionate effect on fix error.

If some UK outstations were re-deployed into Europe or Scandinavia, the Gibraltar and Cyprus outstations would become less critical. Re-deployment of the Cyprus outstation further north onto the European mainland could well improve communications and selected sferic reception, without significantly degrading seven-outstation performance in the southern limits of the service area.

RECEIVER RESOURCE SATURATION

The ATD technique is useable at high data rates and detection efficiencies, but the present system was engineered as an economic replacement for the much slower manual CRDF system.

The current ATD system is limited mainly by control-station processing capability to 400 strokes h^{-1}, averaged over several minutes, although this could be cheaply upgraded. A 'clean' 110 bits s^{-1} communications capacity would become saturated at around 3–6 times this data rate. Resources are limited, so the system is designed to make a semi-randomised selection from all available sferics (including weaker ones) using an outstation analogue threshold, and an adjustable 'dead-time' imposed on the control station after sferic selection [2].

Outstation receivers have two independent gain-settings. One (adjusted by the control station) determines gain between antenna and digitiser circuits, and should be set so that sferics from strokes at 'appropriate' ranges do not saturate the electronics (special circuits 'tag' near-overload and overloaded signals). The other adjusts the threshold above which electric-field waveforms are judged sufficiently 'sferic-like' for their processed signals to be stored — awaiting requests for forwarding from the control station. The latter is adjusted locally to control the volume of data temporarily stored in outstation random access memory (RAM). The control station directly adjusts the 'selector' outstation threshold to adapt control station fixing rates to 400 strokes h^{-1}; thus system detection efficiency is a function of activity [2].

However, an operational practice has crept in whereby control station operators attempt to acquire 'all' sferics from UK strokes (a user ideal) by setting the antenna-to-digitiser gains, and dead-time, to minimum. This causes problems when storms occur near an outstation; because local activity rapidly fills up outstation buffer RAM, raising the threshold, and making the outstation less sensitive — and therefore unavailable to sferics from more distant strokes. The problem is compounded if the control station attempts to fix strokes closely spaced in time (ie. with short dead-time) as the RAM buffer is emptied slowly.

In practice locally-generated data are 'distorted' by unusually short ranges, and so are of little use for *ATD*-extraction. Increasing the antenna-to-digitiser gain to levels appropriate to sferics from more 'normal' ranges will cause most abnormally short-range sferics to overload — and be tagged as such. Overloaded waveforms are currently not reported to the control station; an outstation software modification would ensure that they were discarded without occupying RAM space, while expending minimal outstation resources. This would break the cycle of RAM congestion from local activity, prevent threshold raising, and allow the outstation to continue reporting sferics from distant ranges provided they are not actually masked by simultaneous local activity.

AMBIGUOUS FIXES

Atkinson et al. [6] highlighted the possibility of ambiguous four-station fixes: a potential problem for both ATD and Time of Arrival (TOA) systems [7], although soluble by appropriate outstation deployment. A 'flat-earth' discussion is presented below.

If two intersecting lines can be drawn through

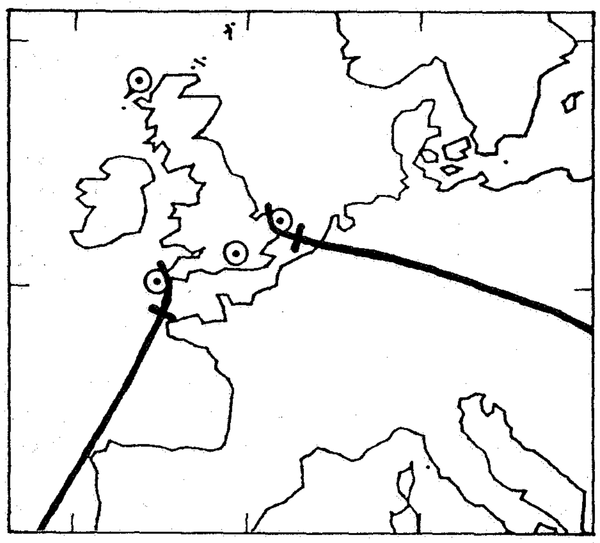

Figure 3: Two ambiguous paired loci for the four Outstations Camborne, Beaufort Park, Hemsby and Stornoway. The divergent paired loci are crossed at their common coincident-foci 'intersection'. Loci close to the outstations hook around Camborne and Hemsby; while their divergent pairs spread beyond Biscay, and towards south-east Europe.

four outstations, all lying on one side of a third line through the intersection, then the two lines may be considered as a limiting pair of hyperbolae with coincident foci at the intersection. In this case, a family of 'four-station' hyperbolae may be drawn with all members having one hyperbola passing through the four outstations; and the hyperbolic foci follow loci diverging from the intersection point.

For any point on a hyperbola, the difference between focal distances is constant. Thus it may be shown that a zero-*RESIDUAL* fix at the focus of one four-station hyperbola is ambiguous with a similar fix at the other focus. This holds for all family members, so any fix lying on a focal locus is ambiguous with a paired focus on the opposite focal locus, and cannot be distinguished by time-difference (*ATD* or *TOA*) alone.

Similar ambiguous fix loci exist over a curved earth. Fig. 3 illustrates two sets of divergent loci for fixes obtained using the four UK outstations shown (five as currently deployed, less Lerwick). Similar loci occur for the five UK outstations less Stornoway — the 'hooks' scarcely move, and the loci are rotated slightly clockwise. Strokes located on the lengthy half-loci are ambiguous (for the four-outstation sets cited) with fixes near the UK on the shorter half-loci, and vice versa.

In practice, apart from 'near coincident' ambiguities close to the intersection point, ambiguous fixes are widely spaced — and can be distinguished through relative outstation amplitudes or waveshapes.

Low $\sigma(r)$ values would make it easier to distinguish non-zero *RESIDUAL* fixes in the vicinity of the loci. In the current system the potential problem areas are known, and fixes found in an ambiguous region are explored by starting the search minimiser (1) near both ambiguous fixes and inspecting the result. A fix is reported when only one solution is likely. The problem is best resolved by having further outstation observations — an option not readily available with short-range outstations.

Deploying three of the outstations in a triangle with the fourth near the centroid prevents the intersecting lines being drawable. Note from Fig. 1 that this is the UK outstation situation when the Beaufort Park outstation is finally deployed at Aughton, whichever of the two northern outstations is lost.

SPURIOUS FIXES

Under unfavourable circumstances, particularly when the above effects conspire to reduce outstation observations, the system makes occasional grossly incorrect fixes — as opposed to fixes with errors comparable to the estimated error based on $\sigma(r)$ values and fixing geometry. These appear to be associated with undetected cycle mis-matches, sometimes in conjunction with the current ambiguous fix mechanism (there is some evidence of identified spurious fixes in the UK area preferentially occurring near the ambiguous fix loci).

During the Jul–Sep 1989 operational trial, particular care was taken to identify 'spurious fixes' which did not correlate with other meteorological evidence:

- Positively identified spurious fixes (mainly near the UK) represented around 0.004% of the total number of fixes [8].

The proportion is small, but forecasters see this as the most significant problem for the current ATD system, because of the resulting loss of confidence. The current system's low detection efficiency was of much lower concern.

ATD SYSTEM HEALTH MONITORING

Indices of overall system health, derived from (1), were designed into the ATD system; not all are currently in routine use.

- Setting $\sigma(r)$ values in (1) to non-dimensional unity makes $RESIDUAL^2$ a measure of $\sigma(r)^2$, to be filtered, displayed as mean $\sigma(r)$, and used for fixing.

The algorithm must avoid 'downweighting' procedures, if necessary re-selecting correlation peaks. Reducing bias improves $\sigma(r)$, and quality control — including cycle-slippage detection.

- Setting $\sigma(r)$ values in (1) to measured averages allows the significance of *RESIDUAL* to be evaluated realistically, and automatically, for each stroke.

The algorithm is based on an F-test. Outliers (at, say, 0.5% or 0.1% significance level) should be rejected, ensuring normal population fixes. Significance levels should be scrutinised, and any tendency to frequent high significance investigated.

Measured $\sigma(r)$ values allow error ellipses to be evaluated. Strokes with fix errors outside agreed limits for their position are rejected, or tagged. Currently default $\sigma(r)$ values of 13 μs are used, making the estimate sensitive to fix location and available data, but not to scaling for *ATD* uncertainty.

- Estimation of bias, and scatter $\sigma(r)$, allow long-term estimates of corrections for bias-reduction, and resolution of epoch ambiguity; and estimates of irreducible scatter.

Plots of average $\sigma(r)$, three forms, provide an overall 'health score'. Degradation requires immediate warning, diagnosis, and remedy. In the system design many potential degradations were automatically maintained, but not all mechanisms are used:

Several epoch sources are provided, including Loran-C and Omega (different ambiguity periods) and inter-comparison techniques; as are automatic means for detecting and responding to hardware timescale jumps. Bias-estimation also detects timescale changes. Recently, NAVSTAR has been added to some outstations. However, operators have tended to use only one epoch source, and have become vulnerable to its weaknesses. Loran-C cycle-slippages of 10 μs have been common — although these are easily detected ([3], Appendix A) and corrected.

The design included automatic closed-loop monitoring and correction of deficiencies in hardware filters. This has not been properly integrated.

Electronically variable notch filters are provided to protect distant (weak) sferics from man-made transmissions. Currently, they are little used.

COMPARATIVE SYSTEM RESULTS

The following studies of comparative fixes and 'detection efficiencies' estimated during Jul–Sep 1989 are detailed by Atkinson and Kitchen [8]; only a summary is presented here.

WMO SYNOP REPORTS

Observer thunderstorm reports (WMO SYNOP present weather codes 17, 29, 91–99) at three-hourly intervals were plotted over the service area, together with comparable ATD fixes. A thunderstorm 'detection index' was defined as the percentage of SYNOP thunderstorm observations for which there was an ATD fix within 100 km. For synoptic purposes it is unnecessary to detect each thunderstorm cell: 'areas' of activity are adequate. Different criteria may be important for short-term forecasting.

Over the entire service area, the two-weekly average detection index was close to the 80% mean, although wider variations occurred on shorter timescales. Over the UK and near continent the index was >90%, falling to less than 50% at the edges of the service area in Eastern and Northern Europe and North Africa. Detection efficiency depends on threshold gain, and areas of distant activity may be masked due to system saturation by nearby storms.

UK ERDC SYSTEM

Within the UK, the five UK-outstation ATD network offers <2.5 km fix errors (assuming 5 μs *ATD* errors), improving to 1.1 km for a seven-outstation network. Predicted scatter should be a factor of 5/1.5 or 3.3 smaller.

Fix comparisons (based on strokes at corresponding times) were made with the Electricity Research and Development Centre (ERDC) 1 kHz direction-finding network [9]. Initial results on Humberside and Leicestershire storms (150 km from two operating ERDC outstations) showed ATD fixes biased 6 km south-west of ERDC fixes. Comparisons with data over the North Sea suggested systematic ERDC bearing errors of a few degrees on this day, so bias was removed to plot scatter comparisons.

The ATD system estimated absolute errors for each fix, based on (probably pessimistic) assumed 13 μs *ATD* errors, were typically 3–10 km for these fixes which included some Gibraltar and Cyprus data. If 1.5 μs *ATD* scatter is assumed, the fix scatter should be a factor 13/1.5 smaller, or 0.4–1.2 km.

Bias-removed results gave 8.5 km standard deviation for ERDC-ATD fix discrepancies <30 km. KEMA-ATD scatter (below) was similar in an area where predicted ATD system scatter was much larger, suggesting that ERDC-ATD scatter is largely attributable to the ERDC system.

The ERDC system's high detection rate allows an estimate of ATD system stroke detection efficiency. During a two-hour period, 46 strokes were seen by both systems, from 53 ATD fixes and 168 ERDC fixes. This suggests an ATD detection efficiency of 27% for ERDC-detected strokes, with ATD selector at Camborne having 21 dB threshold gain. Flash detection efficiency may be a little higher if ERDC detected multiple strokes. Similarly, the ERDC detected only 87% of the ATD fixes, although this could be because it is less sensitive to cloud-flashes than the ATD system.

NORWEGIAN TRANSINOR SYSTEM

The TransiNor system uses 18 LLP magnetic direction-finding outstations [10,11], operating in Norway, Denmark, Sweden, and Finland. Fix times identified corresponding strokes, and fix comparisons were made mainly in southern Norway. TransiNor fixes can be made with up to eight outstations, although most used only 2–3.

In this northern region few ATD data from Gibraltar or Cyprus were available. Fig. 2 indicates that the five UK outstations alone, assuming $\sigma(r) = 5$ μs *ATD* error, give fix errors in southern Norway of 12–26 km. However, the current system does not estimate $\sigma(r)$, so the default value of 13 μs was assumed — to estimate a (probably pessimistic) 30–60 km error for ATD system fixes.

The normal population discrepancies between ATD and TransiNor fixes varied widely: the largest were for oceanic TransiNor fixes to the south-west of Norway. However, these used just two TransiNor stations at Oslo and Satenas; the latter appearing to give bearing errors varying with azimuth, as found by Schutte et al [12], implying dominant TransiNor errors. More typically, fix discrepancies were around 65 km; although it is believed that the TransiNor system contributed a sizeable portion as there appeared to be little correlation between estimated ATD fix error and fix discrepancy. Other occasions gave rather lower discrepancies — down to 35 km.

LLP observations were used to deduce ATD system detection efficiency. In Southern Norway on 8 Aug, the apparent stroke detection efficiency (based on TransiNor detections) was 25% between 0900–1200 GMT (at a selector threshold gain of 21 dB), falling to 13% from 1200–1500 GMT (threshold gain 15 dB). These may be slight under-estimates of flash detection efficiency, as some TransiNor strokes were part of multiple-strokes, but are otherwise broadly typical.

DUTCH KEMA SYSTEM

Keuring van Elektrotechnische Materialen (KEMA) operate a 5-outstation LPATS network [7], and local fixes were studied at 52.5–54 N and 3–4.5 E. The ±1.5 s LPATS timescale uncertainty caused difficulties, but comparisons were made with ATD system fixes.

ATD system accuracy depends on available outstations: seven (and assumed 5 μs *ATD* error) imply fix errors of 1–1.5 km; degraded to 5–12 km with only five UK outstations, which was more typical.

Initial comparisons highlighted an 8 km bias between ATD and KEMA fixes, mainly through a 10 μs Loran-C zero-crossing error in the Stornoway timescale. The ATD fixes appeared more spread geographically than KEMA fixes, suggesting KEMA fixes in this area are more precise, as might be expected for the five-outstation ATD network.

The bias was removed, and resulting fix discrepancies found to fit a distribution with a standard deviation 8.5 km for discrepancies less than 30 km.

This ATD system result suggests useful accuracy consistent with predicted absolute fix errors in this area, but is slightly disappointing as scatter appears larger than the 2–5 km that might have been expected from an assumed 2 μs *ATD* scatter.

LPATS timing problems compromised estimates of ATD system stroke detection efficiency, but with a Camborne selector gain of 21 dB this was around 25%, in agreement with above estimates.

FLORIDA ARSI SYSTEM

Atmospheric Research Systems Inc (ARSI) manufacture the LPATS system, and operate a five-outstation network covering 24–32 N, 85–77 W. Both ATD and ARSI systems observed a storm 200–300 km off the east coast of Florida for a mid-day path on 14 Sep, 1979. Agreement in absolute fix positions was fair, with discrepancies <100 km — although an assumed 5 μs *ATD* error would have suggested a 36 km error. ATD system detection efficiency was only a few percent at this range, and only 8 coincidences were observed.

Assuming 'correct' ARSI fixes, the measured *ATD* values (from Beaufort Park) were compared with theoretical ones. This highlighted 10 μs timescale biases at two outstations (Loran-C!). More importantly, although the random difference between *ATD* values was 2–3 μs at most outstations, the Lerwick value was around 6 μs. This is larger than expected, is inconsistent with observed propagation effects ([3] Appendix A), and was not observed at 'nearby' Stornoway. This may imply a fault or local influence at Lerwick, perhaps explaining the over-large scatter in KEMA comparisons. This is being investigated.

LOOKING AHEAD

For the ATD system we have:

	UK Area	Wide Area
• Absolute $\sigma(r)$:	3–7 μs	3–7 μs
Relative $\sigma(r)$:	1.3–1.6 μs	1.3–2.0 μs

The above $\sigma(r)$ errors have been estimated, and Figs. 1, 2 relate these to fix errors. Absolute errors can be reduced to make the system less vulnerable to outstation loss. Quality needs protection by tightening identified closed-loop procedures. Accidental timescale misalignments (by ambiguities of 10 μs) have been common, but are easily detected by available techniques, especially if bias is reduced. A possible problem with Lerwick is currently being investigated.

- Comparisons with KEMA and ARSI systems lend credence to $\sigma(r)$ fix error estimates. ERDC and TransiNor comparison discrepancies are probably dominated by the comparison system.
- Fix errors become degraded if outstations are unavailable. This currently happens through communications problems, poor outstation deployment, and receiver resource saturation. All are tractable problems.
- A combination of poor outstation deployment, unavailable outstations, and bias-degraded $\sigma(r)$ leads to a spurious fix rate of 0.004%. Although not large, this is considered the most important system problem for the forecaster. Improvements are achievable in all causative areas.
- Stroke detection efficiencies are low at around 25% near the UK, although adequate for synoptic purposes. Nevertheless, higher detection efficiency is desirable — and is achievable through improved processing (and possibly communications) resources.

The system can be upgraded. Trade-offs between real benefits and increased costs need to be considered.

ACKNOWLEDGEMENTS

My thanks are due to N.C. Atkinson for discussions, and for sight of the draft paper by Atkinson and Kitchen, and to M.R. Blackburn. The comparisons summarised here are largely the work of N.C. Atkinson, M. Kitchen, and R. Johnson who have studied operational aspects of the ATD system.

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